The HART-II Test: Rotor Wakes and Aeroacoustics with Higher-Harmonic Pitch Control (HHC) Inputs
- The Joint German/French/Dutch/US Project -

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Abstract

In a major cooperative program within the existing US-German and US-French Memoranda of Understanding/Agreements (MOU/MOA), researchers from German DLR, French ONERA, NASA Langley, and the US Army Aeroflightdynamics Directorate (AFDD) conducted a comprehensive experimental program in October 2001 with a 40%-geometrically and aeroelastically scaled model of a BO-105 main rotor in the open-jet anechoic test section of the German-Dutch Windtunnel (DNW). This international cooperative program carries the acronym HART-II (Higher harmonic control Aeroacoustics Rotor Test).

The main objective of the program is to improve the basic understanding and the analytical modeling capabilities of rotor blade-vortex interaction noise with and without higher harmonic pitch control (HHC) inputs, particularly the effect of rotor wakes on rotor noise and vibration. Comprehensive acoustic, rotor wakes, aerodynamic, and blade deformation data were obtained with pressure-instrumented blades. The test plan has been concentrated on measuring extensive rotor wakes with a 3-component Particle Image Velocimetry (PIV) technique, along with measurements of acoustics, blade surface pressures, and blade deformations.

The prediction team with researchers from DLR, ONERA, NASA-Langley and AFDD was actively involved with the pre-test activities to formulate a test plan and measurement areas of the PIV technique. The prediction team predicted all the test results in advance before performing the wind tunnel test. This was done to obtain the best quality of test data, to improve the speed of measurements, and to determine the necessary measurement information for code validation. In this paper, an overview of the HART-II program and some representative measured and predicted results are presented.

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Introduction

Among several helicopter noise generating mechanisms, blade-vortex interactions (BVI) cause one of the most annoying and intrusive kinds of noise and become dominant during low speed descent and maneuvering flight, where the rotor wake is blown back into the rotor plane.

Recent research efforts in Germany, France, and the US have indicated a potentially high payoff on both noise and vibration reduction by the application of a higher-harmonic blade pitch control (HHC) technique. Although originally designed and developed for vibration reduction, several wind tunnel tests and flight tests have shown noise reduction of up to 10 dB with the application of HHC inputs, while vibration and low-frequency noise levels were increased (Ref. 1 - 7). However, with certain HHC schedules (amplitude and phase), the simultaneous reduction of noise and vibration has been achieved. But better physical understanding and analytical models are necessary to explain the basic physics of the noise/vibration reduction. Since the current physical understanding of the HHC effect on noise and vibration reduction is still limited, the full potential of the technique has not been fully utilized. For further improvements of the physical understandings, the international rotorcraft research community has recognized the essential needs of the development of advanced analytical prediction capabilities and also a comprehensive database.

In 1994, researchers from German DLR, French ONERA, NASA Langley, and the US Army Aeroflightdynamics Directorate (AFDD) conducted the first HART (Higher-harmonic Aeroacoustics Rotor Test) program with a 40%-geometrically and aeroelastically scaled model of a BO-105 main rotor in the open-jet anechoic test section of the German-Dutch Windtunnel (DNW) (Refs. 8 - 14). In this first HART program, extensive measurements of acoustics, blade pressures, and blade deformations were made as well as some limited rotor wake measurements. Rotor wake measurements were made with a 3-component Laser Doppler Velocimetry (LDV) technique at only one azimuth angle on the advancing side and at another angle on the retreating side due to wind tunnel time constraints and limitations of experimental techniques at that time.

Due to lack of comprehensive wake information, the HART team decided to conduct a second test with the emphasis on wake measurements using a 3-component Particle Image Velocimetry (PIV) technique that provides instantaneous velocity vectors (Refs. 15 and 16). Two teams were formed to efficiently carry out the program: a test team and a prediction team consisting of researchers from each participating organizations.

The test team, coordinated by the Institute of Flight Systems, DLR, Braunschweig, Germany, carried out the test in the DNW along with data acquisition/analysis responsibility (Ref. 17). The prediction team, coordinated by NASA Langley Research Center, with researchers from DLR, ONERA, NASA-Langley, and AFDD, developed their own prediction capability in acoustics, aerodynamics, free wake system, and blade deformation (Refs. 18, 19 and 23). This prediction team was actively involved with the pre-test activities together with the test team to define the measurement approaches of the techniques. Specifically, the prediction team activity was (1) to correlate its predicted results with the existing HART-I data, (2) to develop and coordinate with the test team to define the HART-II test matrix, and (3) to predict the HART-II test results in advance. This was to ensure obtaining the best quality of test data and the necessary information for the code validation.

The responsibilities of the participating organizations were as follows.

DLR - Flight Systems:

- Test team activity coordination
- Rotor test rig and related hardware
- Rotor operation, rotor and balance data acquisition and analysis

DLR – Flow Technology:

- 3-component Particle Image Velocimetry (PIV) (small, high-resolution window)

DLR – Aeroelasticity

- Blade pressure measurements

NASA – Langley Research Center

- Prediction team activity coordination
- Analytical prediction capability

ONERA: Analytical prediction capability

DNW:

- 3-component PIV (large, low resolution window)
- Stereo Pattern Recognition (SPR), Blade Tip Deflection (BTD)

- Acoustic measurements and analysis, rotor position measurement

AFDD:
- Analytical prediction capability
- Overall program coordination

The main objective of the program was to measure detailed rotor wakes for a normal descent flight condition with and without higher-harmonic pitch control inputs. Through this wake database, the physical understanding and analytical modeling can be improved for BVI noise/vibration generating mechanisms. With validated analytical models, the effect of wake systems on blade airloads/noise and the effect of higher-harmonic pitch controls on rotor noise/vibration reduction can be thoroughly investigated.

Three test cases were mainly concentrated with extensive rotor wake measurements using a Particle Image Velocimetry (PIV) technique: a baseline case without HHC inputs, a minimum noise case and a minimum vibration case with 3/rev pitch control. The general information on the test is available in Ref. 17. In this paper, an overview of the HART-II program and some representative experimental and predicted results are discussed.

Test Facilities and Rotor Operation

The DNW is the world's largest acoustic wind tunnel and has outstanding aerodynamic and acoustic properties with low background noise. The DNW has become a major rotorcraft aeroacoustic testing facility. All the data acquired for this program were taken in the 6.0 by 8.0 m open-jet configuration, where flow velocities of up to 80 m/s (262.5 ft/sec or 155 knots) can be reached. An acoustically treated testing hall of more than 30,000 cubic meter surrounds the open-jet testing configuration. This results in exceptional anechoic properties (the cutoff frequency is 80 Hz). The tunnel also has excellent flow qualities, since the flow uniformity is quite high and the unsteady disturbance amplitude is quite low over the total testing velocity range.

The BO-105 model rotor was positioned on the vertical and lateral centering of the DNW test section, and up one meter from the longitudinal centerline (Fig. 1). This position enabled acoustic measurements for the acoustic traversing mechanism located inside of the tunnel shear layer. The newly designed rotor test rig ROTEST II features high-frequency hydraulic rotor control actuators for the higher harmonic rotor control. The test rig contains the hydraulic drive system, the rotor balance, and was supported by the computer-controlled, hydraulically actuated model sting support mechanism of the DNW.

The rotor was controlled by three electro-hydraulic actuators below the swashplate for HHC capabilities. The higher-harmonic pitch controls were achieved by superimposing 3/rev-swashplate motions in addition to the trim collective and cyclic pitch controls. For this test, open loop higher-harmonic pitch control inputs were manually provided for amplitude and phase shift. For a given flight condition, a trim with zero pitch and roll moments was first achieved with proper collective and cyclic controls. Then, a 3/rev pitch control was superimposed to the trim condition with a different phase value (ψ_3), depending on minimum noise and vibration case, along with a given pitch amplitude, and the rotor was re-trimmed to the desired condition.

The test condition was for 6^0 descent flight at μ= 0.15, which is a typical noise certification condition for maximum BVI noise radiation. Three cases were mainly concentrated for extensive wake measurements at this time: a baseline case without HHC inputs (BL, $\psi_3 = 0^0$) and two 3/rev HHC inputs with different phase shifts of a minimum noise case (MN, $\psi_3 = 300^0$) and a minimum vibration case (MV, $\psi_3 = 180^0$). The amplitude of the HHC input controls is 0.8^0. More detailed information is available in Ref. 17.

The rotor is a 40%-geometrically and dynamically scaled model of the 4-blade, hingeless BO-105 main rotor of 4m diameter and 0.121m chord length. The rotor blade uses a NACA 23012 airfoil with the trailing edge modified to form a 5 mm long tab to match the full-scale rotor. This

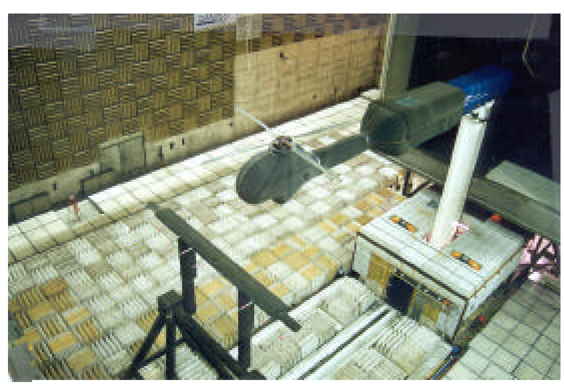

Fig. 1 BO-105 model rotor in the DNW

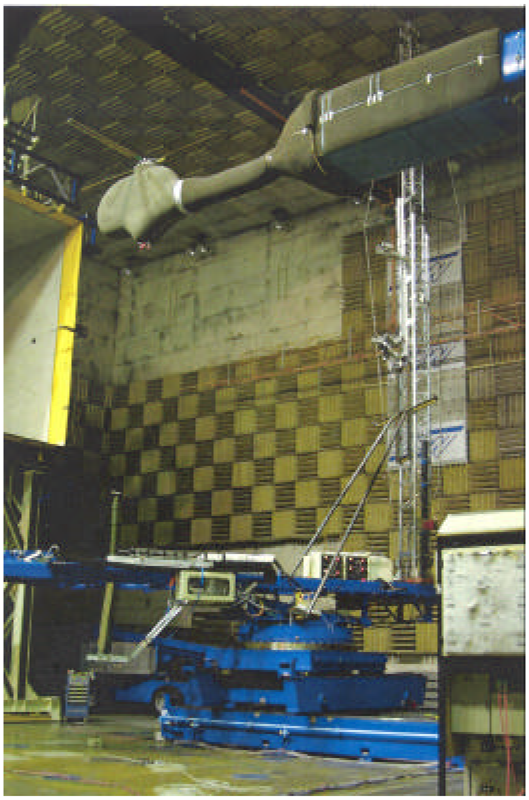

Fig.2. PIV setup at the DNW

rectangular blade has - 8 deg. of linear twist, a square tip, and a solidity of 0.077. The nominal rotor operational speed is 1041 rpm, giving a blade passage frequency of 70 Hz. The nominal hover tip Mach number is 0.641. More detailed information on the rotor characteristics is given in Ref. 17.

Since the rotor model used in the first HART test was not available for the HART-II test, two rotor blades of another BO-105 model rotor were equipped with a total of 51 specially configured miniature absolute pressure transducers of the piezoresistive type, mainly installed at a blade spanwise location at r/R = 0.87. At this location, the section was fully equipped for aerodynamic loading analysis, the surrounding at the leading edge was densely instrumented for turbulence analysis, and the leading edge has sensors between r/R= 0.4 and 0.97 for BVI location analysis. The typical response was flat within 1 dB up to 7 kHz with a resonance occurring beyond 20 kHz. Two blades were also equipped with blade pitch sensors, and each of the four blades had six strain gauge pairs at the root: three for flap, two for lead-lag, and one for torsion.

Representative Test and Predicted Results

Tip vortex geometry:

Extensive measurements of the rotor wake were obtained by a 3-component Particle Image Velocimetry (PIV) technique (Ref. 16), including tip vortex geometry and vortex structures over the entire rotor disk. From the PIV vector maps, the details of the vortices, such as core size, strength, and circulation, will be determined as a function of wake age. The PIV system consists of five digital cameras and three double pulse Nd:YAG lasers with 2x320mJ each, which were mounted on a common traversing system in order to keep the distance between the cameras and the light sheet

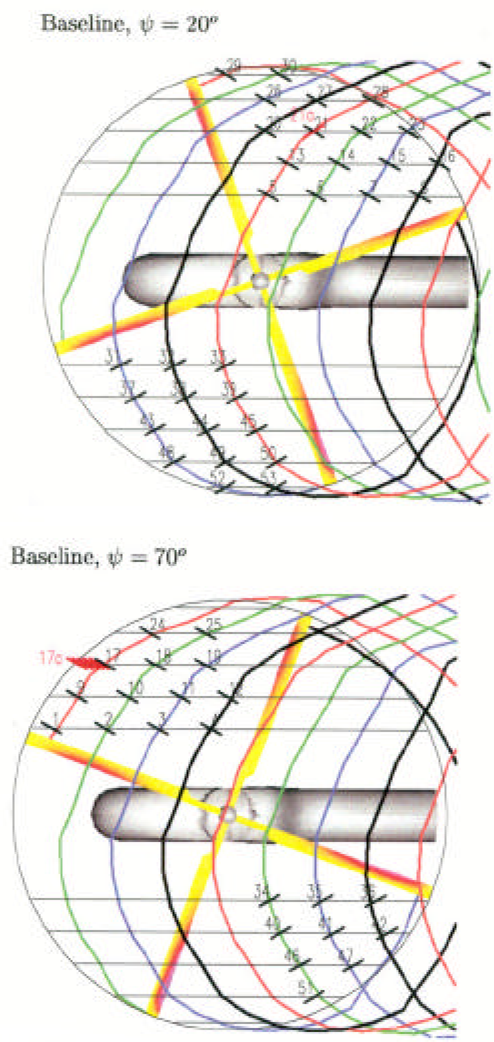

Fig.3. Wake measurement positions

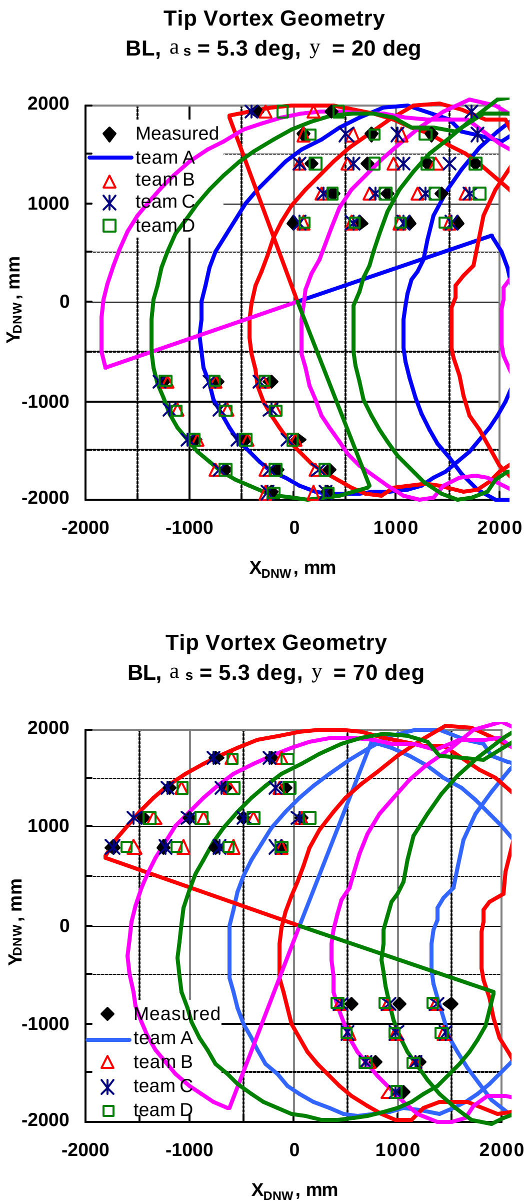

Fig. 4. Top views of the tip vortex geometry for the baseline case at two azimuth locations (measured data vs. predicted results)

constant while scanning the rotor wake as shown in Fig. 2. The cameras were located on the 15m vertical tower, both above and below the rotor plane and the lasers were located underneath the rotor. The length of the traversing system was on the order of 10m. About 500-giga byte of PIV raw data was recorded at many positions on the advancing and the retreating sides.

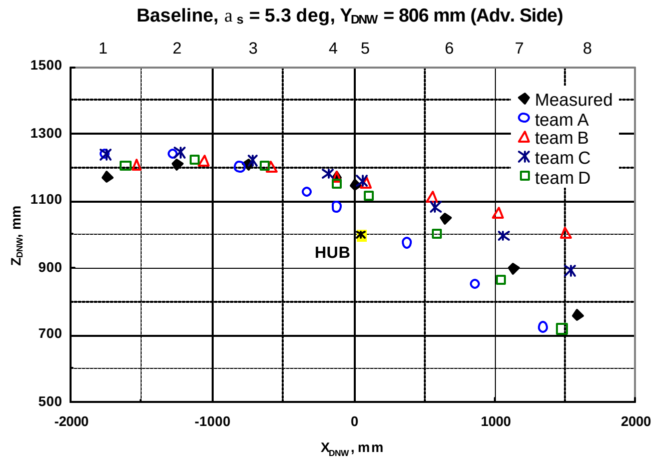

Fig. 5. Side view of the tip vortex geometry for the baseline case (measured data vs. predicted results)

The PIV measurements were obtained for about 50 locations on both the advancing and retreating side with the reference blade at $\psi = 20^o$ and 70^o as shown in Fig.3. The measurements and predicted results of the tip vortex geometry for the baseline case are shown in Fig. 4 and 5. These results were predicted by the HART team members and were generated before the test.

Vortex Structures and Core Size:

From the 3-component velocity vector maps the wake structure will be determined. A typical instantaneous vortex velocity map is shown in Fig.6. The velocity fields for the baseline case show that the vortex structures on the retreating side are well focused, while the vortex structures on the advancing side are less focused in part due to multiple close interactions on its way downstream. For the MV case, the velocity field clearly shows the double vortices due to the negative lift on the blade tip region in the second quadrant.

Before an analysis of the vortex properties, the coordinates and velocities have to be transformed into the vortex axis coordinate system. Then by taking a horizontal cut through the location of maximum vorticity, the instantaneous tangential velocity field will be obtained. From tangential velocity fields, the vortex core size will be determined from the distance between two maximum tangential velocities. The development of vortex structures, such as core size, roll-up and aging process, along the downstream over the two

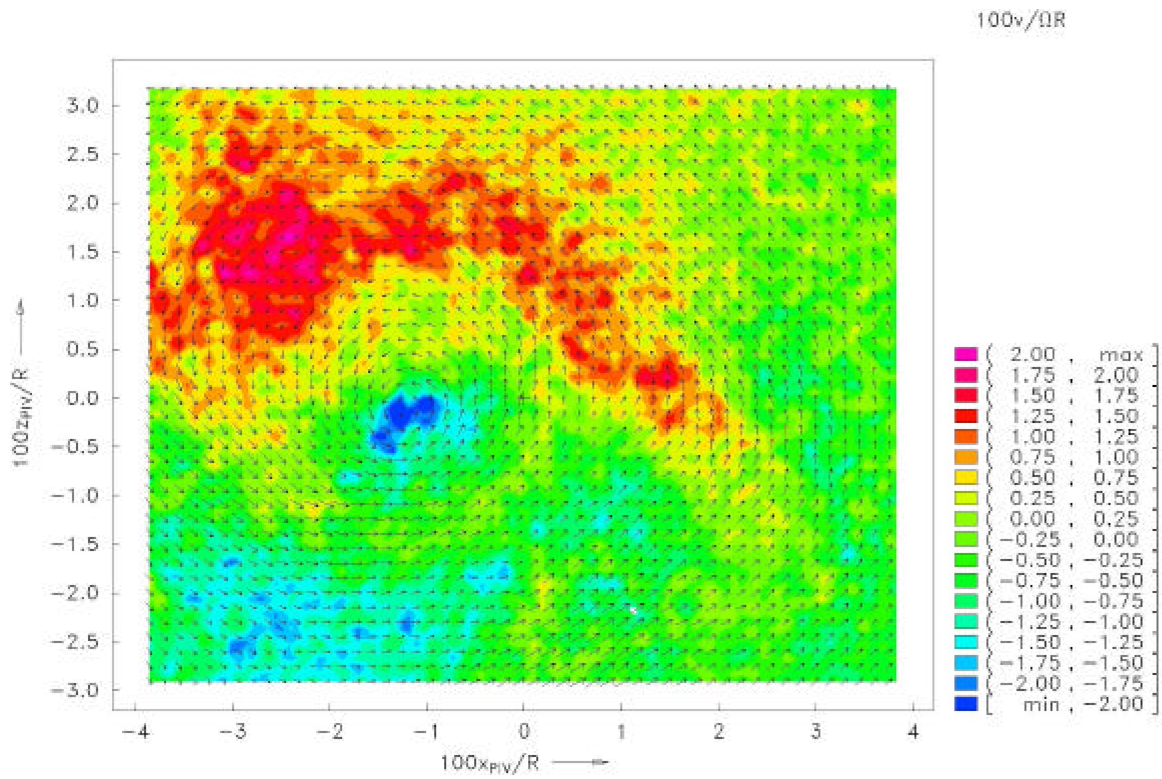

Fig. 6. Typical vortex velocity field from PIV measurements

blade-revolutions from generation will be carefully investigated from this database. In addition, the blade-vortex miss distance for each interaction will also be investigated along with the measurements of blade flapping deflection. More detailed information about PIV measurements will be available in Refs. 16 - 18.

Airloads:

Sectional blade airloads (C_N) were calculated by integrating the measured blade pressures at the fully instrumented radial station of 87%. The non-dimensional normal force, C_N M^2, at the span location of 87% (r/R = 0.87) is plotted along with the azimuth angle (ψ) as shown in Fig. 7, which shows distinct loading fluctuations due to BVIs on the advancing and retreating sides. As observed at the HART-I test, strong changes of the blade airloads were shown with higher-harmonic pitch control inputs, such as a distinct smoothing of the airload fluctuations for the minimum noise case and multiple strong fluctuations for the minimum vibration case.

From the minimum noise case (Fig.7b) where the airload is increased in the second quadrant, the circulation of the trailing tip vortex seems enlarged and the induced velocity seems increased. Due to this increased induced velocity and also the blade flapping deflection, the miss distance between the tip vortex and the rotor blade at the interaction is increased as will be shown later. For the minimum vibration case (Fig. 7c), nearly opposite trends can be observed. The sectional airloads are decreased to negative lift on the blade tip region in the second quadrant, which decreased induced velocity or even generated upwash velocity. This will reduce the miss distance significantly and even push the tip vortex upwards above the rotor plane, which shows multiple airload fluctuations on the advancing side. This in turn significantly increases the noise radiation while vibration levels are low. Furthermore, the negative lift on the blade tip region on the advancing side may generate a double vortex system that was observed with a flow visualization technique in the first HART test (Ref. 14) and measured by the PIV technique in this HART-II. The double vortices are generally consisted of counter-clockwise at the tip and clockwise inboard, due to a spanwise bound circulation distribution with strong radial gradients at the tip and also with opposite sign somewhere inboard.

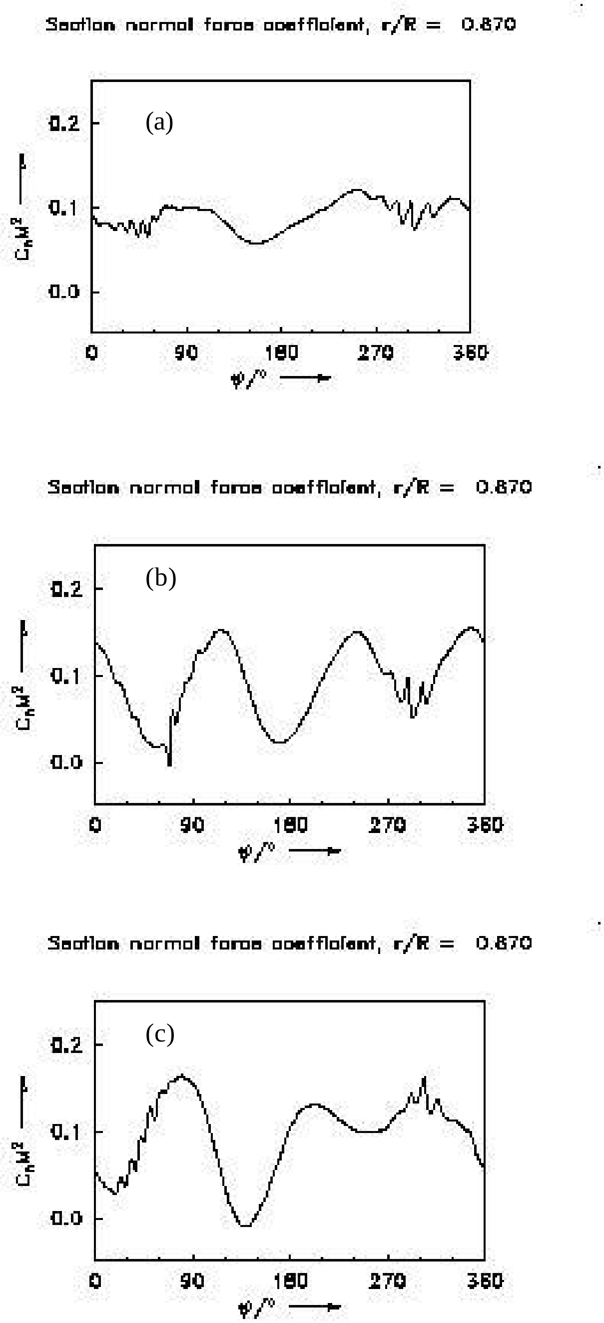

Fig. 7 Blade Airloads for baseline (a), MN (b), and MV (c) cases at r/R = 0.87

One peculiar phenomenon for the baseline case is the 2/rev variation in the airloads as shown in Fig.7a. This 2/rev variation is currently not explainable with the current understandings and is not duplicated by current analytical codes as shown in Fig.8 (Ref.19), where the predicted results have been substantially improved by using the measured blade torsion deformation in the analysis.

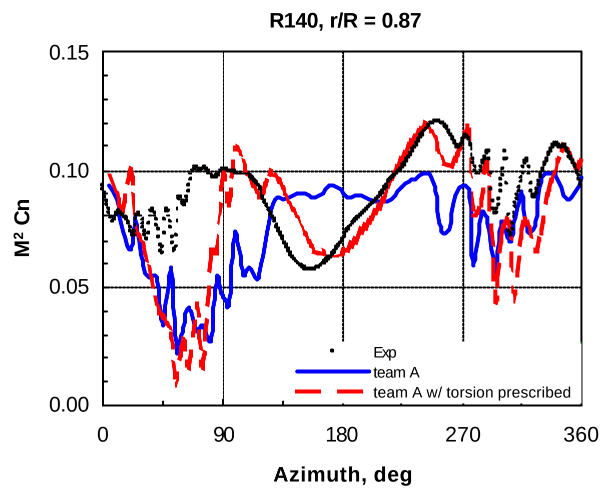

Fig. 8. Predicted and measured airloads fo the baseline case (with and without measure blade torsion deformation)

Blade Deflection:

For a detailed analysis of blade-vortex interactions, it is essential to gain knowledge about the blade deformations. The DNW has developed an advanced optical method, a Stereo Pattern Recognition (SPR), where white markers are taped on the blade painted blade surface and photographed during the test (Ref.22). The technique uses four floor-mounted cameras. Each pair was focused on one half of the rotor disk such that the entire disk could be observed at the same time. All rotor blades had markers on both the leading and trailing edges from 23% span to the blade tip. Data were taken at every 15^0 in azimuth angle. Looking from a different direction to the blades, the position of the markers in space can be evaluated from the two images of a pair of cameras. Detailed information is available in Ref. 17.

The application of this method for operating rotors required that the blades were painted black with white markers and the testing chamber was darkened. The recordings of the blade in motion were carried out with high resolving-power CCD cameras. Furthermore, the calibration images were processed separately and subsequently the results of the separate digital image processing provided absolute marker positions in space. In this way, the pre-twist and the precone angle of the blade were automatically taken care of.

The blade tip deflection was measured using an optical technique, called the Blade Tip Deflection

(BTD) method, by which the images of two reflecting points on the blade tip are recorded at each rotation on a stroboscopic CCD camera. The variations of the blade flapping, lead-lag and pitching of the blade tip are measured as a function of time with a resolution of a few tenths of a millimeter and a few hundredths of a degree. This method was successively applied at two azimuth angles and its results are in very good agreement with those measured by the SPR method.

The flap deflections at the blade tip show very interesting phenomena, particularly at the two azimuth angles: at vortex generation ($\psi = 130^o$) and at blade-vortex interaction ($\psi = 60^o$). For the minimum noise case, the blade flaps down when a tip vortex is generated ($\psi = 130^o$), while the blade flaps up when the tip vortex interacts with a blade ($\psi = 60^o$). This contributes to the increased miss distance for the minimum noise case. The situation is almost exactly opposite for the minimum vibration case, in which there are multiple close blade-vortex interactions (Fig. 9). However, in this case the contribution of the blade flapping deflection to the miss distance seems to be small

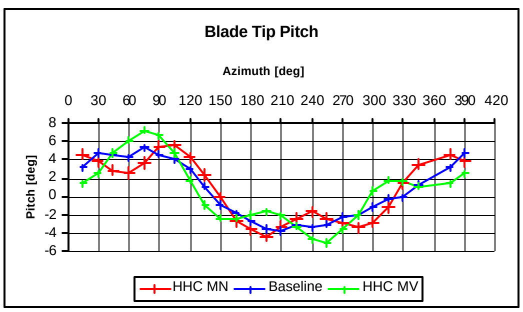

Fig. 9. Blade Tip Pitch variations for baseline, MN, and MV cases

compared to the effect of the induced velocity and related vortex convection. (Refs. 20 and 21)

Acoustics:

The acoustic measurements were made with the array of thirteen ½-inch microphones mounted on a ground based traverse system with a maximum range of 8m in the flow direction. This microphone array was moved slowly and continuously from 4m upstream to 4m downstream from the rotor hub and stopped for a measurement each 0.5m. The array vertical position was 2.3 m (1.15 R) below the rotor hub. The excellent aerodynamic flow quality and acoustic properties of the DNW contributed to both the consistent steadiness and repeatability of the acquired acoustic data.

The noise characteristics of all three test cases were very comparable with those of the HART-I, including noise levels and directivities, even though different rotor blades were used. The details of acoustic measurements and results are in Ref. 14.

Description of Prediction Codes

As part of this cooperative program, comprehensive prediction codes were developed by each participating organization with the emphasis on an understanding of BVI noise generating mechanisms with and without higher-harmonic blade pitch controls.

The DLR rotor code S4 is a comprehensive code for the computation of isolated rotors with high-resolution blade loads for acoustic post-processing. It mainly consists of aerodynamics, structural dynamics and induced velocities modules. These are embedded in a trim algorithm and comprise: (a) the aerodynamic module with nonlinear unsteady lifting line aerodynamics, including Mach effect, dynamic stall, varying velocity effects, and yaw influence, (b) the structural dynamics module with an arbitrary number of articulated or hingeless elastic blades. Each blade is represented by its mode shapes and natural frequencies in flap, lead-lag, and torsion, separately. Within the rotor code, the generalized coordinates of each mode as the dynamic answer to the generalized aerodynamic forcing are computed by time integration of their differential equations of motion. (c) The induced velocities module with either a prescribed tip vortex wake or free-wake is used, together with rotor-body interactions and wind tunnel-body interactions. The overall control is done with an automatic trim module for specified non-rotating hub forces and moments. As degrees of freedom to trim to the desired values, the collective and cyclic controls are used; and in addition the rotor shaft angle of attack is used. The rotor trim is defined by vertical and propulsive force, pitch and roll moment, and the air data like temperature, pressure, and velocity.

The French ONERA uses an aeroacoustic prediction method based on five main steps (Ref.23). In a first step, the HOST (Ref.24) aeromechanics code performs the trim analysis, using the lifting-line theory with a singularity method to describe a vortical wake of prescribed geometry. Then, the initial wake calculated by HOST is distorted by using the free wake method implemented in the MESIR code. An intermediate step between wake and pressure calculation is introduced in the computational chain. It consists of a roll-up model of the vortices (MENTHE code). The blade surface pressures are then calculated by the unsteady singularity method ARHIS, modeling any vortex located close to the blade as a cloud of elementary vortices in order to take into account the vortex deformation during Blade-Vortex Interaction. Finally, the noise radiation is computed by the PARIS code, based on the Ffowcs Williams-Hawkings equation.

NASA Langley uses a CAMRAD.Mod-1 code, which is a rotor performance code with free wake and blade dynamics models. And this is an enhanced version of the CAMRAD code. A high-resolution post processing code, called HIRES, is coupled with CAMRAD. Mod-1. The unsteady full potential code, FPRBVI, is alternately coupled with CAMRAD.Mod-1 to provide blade pressure prediction. With the inputs from FPRBVI/HIRES, the acoustic code, WOP-WOP, was used for acoustic predictions. Furthermore, wind tunnel wall corrections and fuselage effects are also considered in the analysis.

The US Army AFDD uses a Second Generation Comprehensive Helicopter Analysis System (2GCHAS) code for airload prediction. This is a multi-disciplinary comprehensive analysis code with a collection of various finite elements (nonlinear beam, linear beam, rigid body mass, etc.). The advantage of 2GCHAS is that a user can build a complete system by selecting various elements from the input script file without changing source code. Aerodynamics options include linear, non-linear (table look-up) and unsteady aerodynamics (Leishman-Beddoes) models. The aerodynamics wake options include uniform inflow, prescribed wake, free wake, and generalized dynamic wake.

All the acoustic codes used in the program are based on the linear thickness and loading terms of the Ffowcs Williams and Hawkings formulation. More details about these various prediction codes and their capabilities are described in Refs. 11-13. With these codes, a joint validation effort was already performed with two existing DNW rotor test data: one with AH-1/OLS data and the other with BO-105 data.

All codes were used to predict the vortex locations within the rotor disk, thus defining the test matrix and the traversing ranges needed. By use of this database the vortices were found very quickly during the test, which accelerated significantly the measurement procedure.

Concluding Remarks

The second joint international cooperative program was successfully performed with the German DLR, the French ONERA, the German-Dutch DNW, US NASA Langley, and the US Army AFDD to pursue the same technical goals with the combined effort of manpower, expertise and financial resources. This program has achieved two important milestones: comprehensive rotor wake measurements with acoustics, blade dynamics, and blade airloads, and successful international cooperation to work together on the same research goals. This database is extremely valuable and will substantially help the research community for code validation and physical understanding for many years to come.

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A wind tunnel test at the DNW with a rotor system such as this needs lots of devoted and talented researchers and engineers. We all appreciate the unselfish devotion of many people who made this program so successful. A few of the devoted contributors are:

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DNW: Hermann Holthusen
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